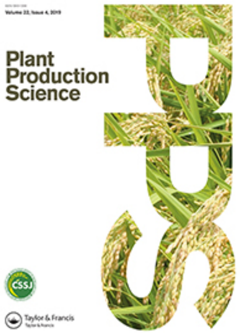

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REVIEW

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Challenges and opportunities for improving N use efficiency for rice production in sub-Saharan Africa

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ABSTRACT

In sub-Saharan Africa (SSA), rice production from smallholder farms is challenged because of a lack of fertilizer inputs and nutrient-poor soils. Therefore, improving nutrient efficiency is particularly important for increasing both fertilizer use and rice yield. This review discusses how to improve the return from fertilizer input in terms of agronomic N use efficiency (AE_N), that is, the increase in grain yield per kg of applied N, for rice production in SSA. The AE_N values we summarized here revealed large spatial variations even within small areas and a certain gap between researcher-led trials and smallholder-managed farms. Experimental results suggest AE_N can be improved by addressing spatial variations in soil-related factors such as P, S, Zn, and Si deficiencies and Fe toxicity in both irrigated and rainfed production systems. In rainfed production systems, differences in small-scale topography are also important which affects AE_N through dynamic changes in hydrology and variations in the contents of soil organic carbon and clay. Although empirical evidence is further needed regarding the relationship between soil properties and responses to fertilizer inputs, recent agricultural advances have generated opportunities for integrating these micro-topographical and soil-related variables into field-specific fertilizer management. These opportunities include UAV (unmanned aerial vehicle) technology to capture microtopography at low cost, database on soil nutrient characteristics at high resolution and more numbers of fertilizer blending facilities across SSA, and interactive decision support tools by use of smartphones on site. Small-dose nursery fertilization can be also alternative approach for improving AE_N in adverse field conditions in SSA.

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Rice; sub-Saharan Africa (SSA); decision support tool; field-specific fertilizer management; agronomic nitrogen use efficiency (AE_N); nutrient-poor soils; small-dose nursery fertilization

ABBREVIATIONS: AE_N: agronomic nitrogen use efficiency; FISP: farm input subsidy program; VCR: value cost ratio; SOC: soil organic carbon; SSA: sub-Saharan Africa; UAV: unmanned aerial vehicle

Field-specific fertilization is a key to improve N use efficiency in rice on heterogeneous and nutrient-poor soils in SSA

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Rice is the most rapidly expanding food commodity both in consumption and production in sub-Saharan Africa (SSA). Rice consumption (milled grain) was more than tripled from 9.2 Mt to 31.5 Mt during the period of 1990 to date in SSA (USDA, 2018). Currently in SSA, rice is the second largest source of caloric intake after maize, and it is anticipated that rice demand will increase continuously given the high rate of population growth and rapid urbanization in the region, which has resulted in a shift in consumer preference in favor of rice (Balasubramanian, Sie, Hijmans & Otsuka, 2007; van Oort et al., 2015).

In response to this growing demand, total rice production in SSA has gradually increased. In the past, this increase was mainly attributed to the expansion of harvested areas (Otsuka & Kalirajan, 2006), although recently it has been attributed to increased yield (Seck, Touré, Coulibaly, Diagne & Wopereis, 2013). Seck et al. (2013) pointed out that the relative contribution of yield to the increase in total production rose to 71% with the high yield growth rate at 108 kg ha^{-1} per year during the period 2007 to 2012, which was equivalent to that achieved by Asian countries during the Green Revolution period (Saito, Dieng, Toure, Somado & Wopereis, 2015a).

However, the average rice yield in SSA is still around 2.1 t ha^{-1}, and a recent database showed that yield growth tended to become stagnant again in the period of 2012–2018 (USDA, 2018). The current yield is far below the potential productivity for rice in the region. The Global Yield Gap and Water productivity Atlas (GYGA) simulated the potential yield of rice (modeled yields with water and nutrients non-limiting and biotic stress effectively controlled) at 7.5–10.8 t ha^{-1} for irrigated lowland production system and water-limited potential yield of rice (modeled yields restricted by solely water supply) at 4.1–8.5 t ha^{-1} for rainfed production systems in major rice-producing countries of SSA (accessed at http://www.yieldgap.org/on Mar13, 2019). Moreover, the gaps between regional rice consumption and production in SSA have continuously widened. The increasing dependency on rice imports has created an economic burden and food insecurity in SSA, and this insecurity became particularly apparent when food riots occurred in several major capitals during 2007–2008 (Berazneva & Lee, 2013). Therefore, further increases in regional rice production remain an urgent priority to ensure food security in SSA.

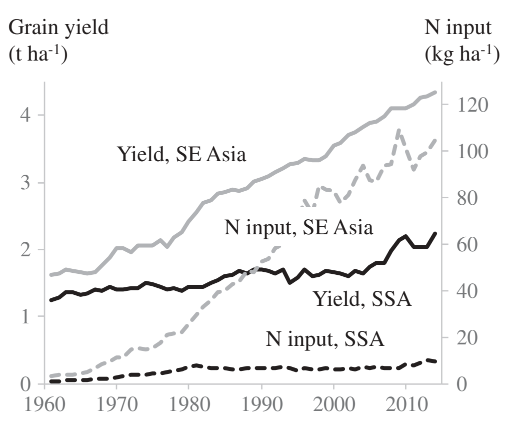

Figure 1. Changes in rice grain yield and mineral N input in southeast Asia (SE Asia) and Sub-Saharan Africa (SSA) from 1961 to present (FAOSTAT).

Previous studies have provided various socioeconomic and biophysical constraints for rice yields in SSA (e.g., Diagne, Amovin-Assagba, Futakuchi & Wopereis, 2013; Kajisa, 2016; Nakano, Bamba, Diagne, Otsuka & Kajisa, 2011; Saito et al., 2013) while it is generally agreed that inadequate fertilizer input and poor soil fertility are major limiting factors to production of not only rice but also other crops in SSA (e.g., Diagne et al., 2013; Haefele et al., 2013; Tittonell & Giller, 2013). Figure 1 compares the annual trends of mineral N application rate, as calculated by dividing total N consumption by total arable land area between Southeast Asia and SSA. Although the N application rates per arable land areas were not equal to those rates per rice harvested area, they were similar in Southeast Asia in 2001 (the N application rates to rice was 76.8 kg ha^{-1}) and in SSA[1] in 1995 to 1998 (the N application rates to rice was 8.9 kg ha^{-1}) (FAO, 2002). The N application rate in Southeast Asia has increased 20-fold, that is, from 5 to 105 kg N ha^{-1}, since 1971, during which time the region achieved substantial increase of rice yield. On the other hand, the N application rate in SSA has remained at less than 10 kg N ha^{-1} until recently, in parallel with the consistently low yield level of rice. These trends are the same for other major nutrient inputs, that is, P and K (data not shown).

Increasing use of fertilizer inputs by local farmers can be only possible if they are available, affordable, and profitable for rice production. The gain in profitability from fertilizer use is often measured by the value cost ratio (VCR), which is calculated as the additional revenue from the fertilizer application divided by its application cost. A VCR of two is the typical benchmark for reliably projecting an increase in profitability for local farmers using mineral fertilizers in SSA (e.g., Xu, Guan, Jayne & Black, 2009; Yanggen, Kelly, Reardon & Naseem, 1998). However, VCR values tend to be low in SSA compared to the other regions worldwide because the fertilizer is more expensive and less accessible owing to the relatively poor development of market and road infrastructures (Minten, Randrianarisoa & Barret, 2007). As many papers pointed out (e.g., Druilhe & Barreiro-Hurlé, 2012), the relatively high fertilizer price and lack of physical access are significant constraints for low mineral fertilizer input in SSA.

Subsidy programs that are geared toward lowering the net cost of fertilizers are one effective means of increasing the VCR for local farmers. Koussoubé and Nauges (2017) argued that subsidy programs can lower a framer's stake in mineral fertilizer, particularly for farmers who are averse to risk and who are uncertain about the best use of fertilizer. For instance, the Farm Input Subsidy Program of Malawi (FISP) has often been cited as a successful case (e.g., Sanzhez, 2015). Dorward and Chirwa (2011) reported that FISP more than doubled the national average yield of maize from less than 1 t ha^{-1} to more than 2 t ha^{-1} as well as the amount of mineral fertilizer input from approximately 0.05 to 0.13 million tons during the period 2005–2006.

However, excessive subsidies can be a burden on the national economies of SSA countries, and hence the cost may outweigh the benefits over the long term as funding for subsidies is typically directed away from other agricultural investments that may have more potential to contribute to sustainable agricultural development (Fan, Gulati & Thorat, 2008; Jayne, Mather, Mason & Ricker-Gilbert, 2013). Zhang et al. (2015) found that excessive subsidies can reduce the efficiency of N use by overdosing N, such as the case in China, or by using fertilizer application into less responsive fields or with inefficient fertilization techniques. Moreover, Marenya and Barret (2009) pointed out that subsidy programs ultimately may not favor poorer farmers because they often cultivate less-fertile soils where crops have a lesser response to applied fertilizer. Ricker-Gilbert and Jayne (2012) reported that households in the bottom 10th percentile of the total crop production value did not have any statistically significant yield increase from the application of fertilizer acquired by FISP. They attributed these low returns for poorer households to their limited landholdings, poor soil fertility, and lack of fertilizer management knowledge. For rice production, Estudillo and Otsuka (2013) pointed out the important role of fertilizer-responsive varieties to enhance fertilizer inputs by local farmers. These arguments strongly suggest that appropriate fertilizer management practices and knowledge should be also provided to enhance yield gains from fertilizer inputs under nutrient-poor soils in SSA rather than only focusing on lowering the cost factor of the VCR.

Therefore, in this paper, we review technical approaches and recent progress toward improving rice responses to fertilizer input. A certain number of studies have been accumulated regarding technical approaches for the improved fertilizer management practices for rice production in SSA, whereas no studies have provided an overview of their quantitative effects and relationship with different production systems and soil conditions. For our purposes, we consistently use agronomic N use efficiency (AE_N), that is, the increase in grain yield per kg of applied N, as an indicator of fertilizer use efficiency because the yield gain from N fertilizer input is the most available dataset and economically meaningful for farmers. First, we review current fertilizer use in terms of the amounts and use efficiencies, that is, AE_N in the major rice-producing regions and for different rice production systems in SSA. Here, we describe rice production in Madagascar to represent low-yield farms with limited fertilizer input and poor soil fertility. Second, we show experimental evidence for how AE_N could be improved by addressing hydrological and soil-related constraints such as phosphorus (P), sulfur (S), and silica (Si) deficiencies, iron toxicities, and low soil organic carbon (SOC) and sandy soils. Third, we discuss plausible technical countermeasures for smallholder farmers to enhance AE_N by giving examples of field-specific nutrient management practices using decision support tools and small-scale fertilizer application in nursery beds.

Genetic improvement that can be adopted to nutrient-deficient conditions is another approach. For example, identification of a P starvation tolerance gene (*PSTOL1*), which enhances early root growth and promotes P uptake (Gamuyao et al., 2012), or of certain QTLs related to internal P use efficiency (Wissuwa et al., 2015), may contribute to the development of rice cultivars that optimize yields from farms with highly P-deficient or P-fixing soils in SSA. Genetic progress in improving root morphological traits, such as steep root angle (Ramalingam, Kamoshita, Deshmukh, Yaginuma & Uga, 2017; Uga et al., 2013), deep rooting (Obara et al., 2010), shallow rooting (Uga et al., 2012), and root plasticity (Owusu-Nketia et al., 2018a, 2018b) can be also applied to nutrient-deficient environments by cultivating rice with root systems that are tailored to the nutrient availability of the local soil profiles. These genetic resources may contribute to higher and consistent returns from N inputs by mitigating other nutrient stresses. However, this approach is not a focus of our review. Further information concerning the progression of these genetic studies can be obtained in recent reviews (e.g., Heuer et al., 2017; Wissuwa, Kretzschmar & Rose, 2016).

Improvement of AE_N in different rice production systems and soil conditions in SSA

Amounts of fertilizer applied

Generally, mineral N use is more prevalent in West Africa compared with East and Southern Africa, which are the two major rice-producing regions in SSA (Saito et al., 2017). A recent cross-sectional survey of 1368 rice fields in 11 countries of West Africa reported that mineral N fertilizer was used in 81% of irrigated lowland fields (average application: 100 kg ha^{-1}), 56% of rainfed lowland fields (65 kg ha^{-1}), and 38% of rainfed upland fields (37 kg ha^{-1}) (Niang et al., 2017). The average N application rate for the irrigated lowland fields in this survey is comparable with the average value for countries in Southeast Asia (FAO, 2002). Other studies have also reported relatively high N application rates in irrigated lowland fields in West Africa, for example, in a range of 72–112 kg ha^{-1} in Benin (Tanaka, Saito, Azoma & Kobayashi, 2013), 134–139 kg ha^{-1} in the Senegal River Valley (Tanaka, Diagne & Saito, 2015), 37–251 kg N ha^{-1} in Mauritania (Haefele, Wopereis, Donovan & Maubuisson, 2001), and 73–147 kg ha^{-1} in Burkina Faso, Mali, and Senegal (Wopereis, Donovan, Nebié, Guindo & N'Diaye, 1999).

Statistically, the percentage of irrigated rice production areas are greater in East and Southern Africa than West Africa, for example, 58% versus 10% in HarvestChoice (2015), whereas mineral fertilizer use remains low even in irrigated lowlands in East and Southern Africa, including Madagascar and Tanzania, which are the second and third largest rice producers in SSA (Haefele et al., 2013; Nhamo, ROdenburg, Zenna, Makombe & Luzi-Kihupi, 2014). In a series of surveys on large-scale irrigation schemes, significantly low N application rates were identified in Uganda (~2 kg ha^{-1}), Mozambique (13–23 kg ha^{-1}), and Tanzania (15–22 kg ha^{-1}) compared to the rates in Burkina Faso, Mali, Niger, and Senegal (>100 kg ha^{-1}) (Nakano et al., 2011; Nakano & Kajisa, 2013; personal communication to Dr. Yuko Nakano on 18 January 2019). For Madagascar, an apparent mistrust of the use of mineral fertilizers for lowland rice production diminished fertilizer use (personal communication to Mr. Ranarivelo Lucien, the Director General of Agriculture in the Ministry of Agriculture and Livestock Madagascar on 5 July 2018). Consequently, mineral fertilizer for rice production in Madagascar is extremely low. Nhamo et al. (2014) also reported that fertilizer application rates were commonly 5–20 kg ha^{-1} for lowland rice production in East and Southern Africa. At least, the yield gap analysis verified equal or slightly greater yield potential and greater yield gaps of irrigated rice production, that is, large opportunities of yield increases with fertilizer inputs still remain in both Madagascar and Tanzania than most areas in West Africa (Saito et al., 2017; Tanaka et al., 2017; van Oort et al., 2015; GYGA at http://www.yieldgap.org/on Mar13, 2019). Therefore, further technical and institutional support may promote fertilizer inputs and yield increases in lowland rice production of these countries.

AE_N in different rice production systems

As observed in surveys across West African countries (Niang et al., 2017), it is logical that farmers prefer to apply mineral fertilizer in irrigated lowlands where more stable returns can be expected relative to drought-prone, rainfed fields. In researcher-led trials in irrigated lowlands in West Africa, AE_N values were in the range of 10–23 kg kg^{-1} (Wopereis et al., 1999), 15–27 kg kg^{-1} (Becker, Johnson, Wopereis & Sow, 2003), and 14–27 kg kg^{-1} (Saito, Azoma & Sié, 2010)—by adopting split N application, adequate weed management, and modern cultivars (Table 1). AE_N data for rice are scarce by reflecting the low adoption of mineral fertilizer inputs in East and Southern Africa. A few studies have reported a range of AE_N at 15–33 kg kg^{-1} in northwest Tanzania (Meertens, Kajiru, Ndege, Enserink & Brouwer, 2003) and 9–31 kg kg^{-1} in the central highland of Madagascar (Nabhan & Rakotomanana, 1990). It should be noted that N application rates in these two studies were relatively low at 30 kg ha^{-1}. AE_N is usually higher at low N rate than at high N rate. Based on experimental results in tropical Asia, Dobermann and Fairhurst (2000) indicated that, with proper crop and water management, AE_N should be typically in the range of 20–25 kg kg^{-1}. The observed AE_N indicated that—at least as reported for researcher-led trials under adequate water management conditions across SSA—the average values were comparable to this range. However, it should be noted that there were large variations in AE_N from location to location within and across these studies.

AE_N values are generally low in rainfed production systems mainly because unstable hydrology restricts the grain yield and response of rice to fertilizer input. Niang et al. (2018) reported that AE_N varied from 7 to 9 kg kg^{-1} as determined by their regression analysis of field surveys and experiments under farmers' management practices in rainfed fields of central Benin. Becker and Johnson (2001) showed even lower AE_N at 3–5 kg kg^{-1} under farmers' management practices and at 6–17 kg kg^{-1} with researcher-led improved management practices in rainfed lowland fields in West Africa. Furthermore, experimental results have clearly demonstrated that AE_N are greater with improved field hydrology in rainfed production systems in West Africa (see *with specific techniques to improve AE_N* in Table 1): Becker and Johnson (2001) reported that the presence of bunds increased AE_N from 4 to 12 kg kg^{-1} in rainfed lowland fields across a range of agro-ecological zones; Touré et al. (2009) reported similar increases in AE_N

Table 1. AE_N values for researcher-led and smallholder-managed farms in different rice production systems in SSA.

Location	Ecology[a]	Operation[b]	N rate (kg ha^{-1})	Treatments for AE_N calculation[c]	AE_N (kg kg^{-1})	Specific management	Specific soil condition	Reference
Multilocational on-farm trials and reports to indicate typical AE_N range in SSA								
Senegal, Mali, Burkina Faso	IL	RM	73–143	NP& none, NPK & none	10–23	Split N		Wopereis et al. (1999)
Côte d'Ivoire, Senegal	IL	RM	60–138	NP& none, NPK & none	15–27	Split N		Becker et al. (2003)
Benin	IL	RM	50–86	NPK & none	14–27	Split N		Saito et al. (2010)
Madagascar	IL	RM	30	NPK & none	9–31	-		Nabhan and Rakotomanana (1990)
Across SSA	IL	FM	120–200	NPK & PK	−1–15	Split N		Saito et al. (2019)
Côte d'Ivoire, Senegal	IL	FM	17–104	NP& none, NPK & none	5–11	-		Becker et al. (2003)
Across SSA	IR, RU, RL	FM	0–191	Regression coefficient	9	-		Tsujimoto et al. (unpublished)
Tanzania	RL	RM	30	N & none	15–33	-		Meertens et al. (2003)
Across SSA	RL	FM	110–200	NPK & PK	3–19	Split N		Saito et al. (2019)
Across SSA	RU	FM	110–160	NPK & PK	5–9	Split N		Saito et al. (2019)
Benin	RU, RL	RM, FM	13–94	Regression coefficient	7–9	-		Niang et al. (2018)
With specific technique to improve AE_Nd								
Côte d'Ivoire	IL	RM	100	NPK (+Zn) & none	6 vs. 11	*Zn supply*	Fe toxicity	Audebert and Fofana (2009)
Madagascar	IL	FM	50	N (+Si) & none	8 vs. 12	*Si supply*		Tsujimoto et al. (unpublished)
Ethiopia	IL	RM	36–105	N (+S) & none	6–10 vs. 14–21	*S supply*		Habtegebrial et al. (2013)
Côte d'Ivoire	RL	RM	60	NPK & PK	1–8 vs. 5–23	*Bunding*		Touré et al. (2009)
Côte d'Ivoire	RL	RM, FM	23–89	N & none	3–5 vs. 6–17	*Bunding*		Becker and Johnson (2001)
Ghana	RL	RM	60	N (+S) & none	1–9 vs. 4–15	*S supply*	Low SOC, sand	Tsujimoto et al. (2017)
Ghana	RL	RM	60	N (+S) & none	11–24 vs. 28–33	*S supply*	High SOC, clay	Tsujimoto et al. (2017)
Ghana	RL	FM	60	N (+S) & none	7 vs. 14	*S supply*		Tsujimoto et al. (unpublished)
Madagascar	RU	FM	50	N (+Si) & none	5 vs. 10	*Si supply*		Tsujimoto et al. (unpublished)
Estimated AE_N with microdose application technique[e]								
Benin	IL	RM	5	NPK & none	110–150	*NPK to nursery*	P deficient	Vandamme et al. (2016)
Cambodia	RL	RM	2.7	NP & none	67–119	*NP to nursery*	Sandy, water-stressed	Ros et al. (2015)
Cambodia	RL	RM	2.7	NP & none	33–78	*NP to nursery*	Sandy, well-watered	Ros et al. (2015)
India	RL	RM	10	NPK &PK	40–211	*N to nursery*	Flood-prone	Panda et al. (1991)
India	RL	RM	4.1	NPK & PK	243	*N to nursery*	Salinity-stressed	Sarangi et al. (2015)

[a]IL: irrigated lowland; RL: rainfed lowland; RU: rainfed upland
[b]RM: researcher-led management; FM: farmer-led management
[c]AE_N was calculated by the yield difference between A & B.
[d]AE_N values are compared without to with specific management.
[e]AE_N are calculated by estimating the equivalent N rate to the main field from the ratio of seeding density to the transplanting density.

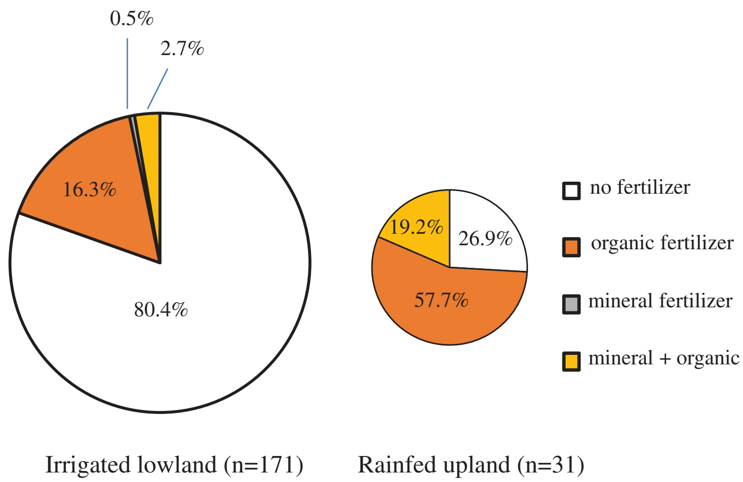

Figure 2. Proportion of farmers applying mineral fertilizer and organic fertilizer for rice production in irrigated lowlands and rainfed uplands in the central highland of Madagascar.

upon bund construction, with a greater effect near the bottom of valleys versus near the top, with a maximum AE_N of up to 22–23 kg kg^{-1} in rainfed inland valleys. The low and unstable AE_N have led farmers away from fertilizer input in rainfed production systems.

AE_N under smallholder-managed fields

Despite a general understanding about low and unstable AE_N in rainfed production systems, one interesting case has been observed in the central highland of Madagascar, where local farmers preferably apply mineral fertilizer for rainfed upland rice rather than irrigated lowland rice (Figure 2). The NPK complex fertilizer was applied to 19% of rainfed upland fields (n = 31) whereas it was applied to merely 3% of lowland fields (n = 171). Farmers explained that this selective application was because the yields of upland rice are too low without fertilizer application whereas they can expect adequate yields without fertilizer in irrigated lowlands. For the upland production systems, their conventional practice of placing a micro-dose mineral and organic fertilizers in each planting hole at seed dibbling may be high in fertilizer use efficiency. Yet, no experimental data exist to compare differences in benefits of fertilizer application between rainfed upland and irrigated lowland fields in the central highland of Madagascar.

This observation implies that agronomic researchers or extension officers should further accumulate empirical evidence for quantitative effect of fertilizer input on rice yields under different farmers' management conditions. Apparently, there is a gap in AE_N between researcher-led trials and smallholder-managed fields (Table 1). Our regression analysis of field surveys, which included 20 irrigated lowland fields, 69 rainfed lowland fields, and 14 rainfed upland fields all under adequate water conditions across SSA, implied relatively low AE_N at 9 ± 3 kg kg^{-1} under farmers' management conditions (unpublished). A recent extensive nutrition trial in a total of 1037 farmers' fields across 30 sites in 17 SSA countries also demonstrated that AE_N values were relatively low even in irrigated lowlands under farmers' management practices (Saito et al., 2019). The average yields with and without N application (NPK vs. PK) were 4.8 t ha^{-1} and 3.4 t ha^{-1} for irrigated lowlands, and for 3.9 t ha^{-1} and 2.5 t ha^{-1} rainfed lowlands, and 3.1 t ha^{-1} and 2.2 t ha^{-1} for rainfed uplands across experimental sites. It should be noted that the N application rates were high in this study which might have lowered AE_N. Nevertheless, the results revealed large variations in AE_N among locations and fields irrespective of rice production systems: the AE_N means were 9 kg kg^{-1} for irrigated lowlands (range—1 to 15 kg kg^{-1}, 12 locations), 10 kg kg^{-1} for rainfed lowlands (range—3 to 19 kg kg^{-1}, 15 locations), and 7 kg kg^{-1} for rainfed uplands (range—5 to 9 kg kg^{-1}, 3 locations). Relatively low AE_N in farmers' fields can be partly caused by suboptimal management practices, e.g., limited weeding frequency, delayed planting, inappropriate timing of fertilizer application, lack of access to fertilizer-responsive varieties, while this tendency can be also attributed to less favorable field conditions, for example, occurrence of micro-nutrient deficiencies and toxicities, poor drainage, extremely sandy or degraded soils that are often avoided from researcher-managed trial sites.

In this regard, identification of factors affecting spatial variation in AE_N at different levels (from location to location or field to field) particularly under farmers' management conditions remains as an important research task. Smallholder farmers require specific information on returns from fertilizer input based on the characteristics of their own fields, that is, as opposed to information pertaining to the average return for the region or for relatively favorable research experimental fields. For example, concerning the irrigated lowlands in the central highland of Madagascar, Nabhan and Rakotomanana (1990) found one field-specific indicator for the AE_N variations, namely that soils having a high content of Fe^{2+} (>200 mg kg^{-1}) tend to have low AE_N. A similar result was observed in the inland valleys of northwest Benin (Worou, Gaiser, Saito, Goldbach & Ewert, 2013). Variations in iron toxicity between fields constitute one soil-related parameter that decreases fertilizer use efficiency in SSA. As exemplified in these studies, soil characteristics are important factors to understand spatial variations in AE_N. In the following sections, we discuss how soil-related factors affect AE_N variations and can be managed to improve AE_N for rice production in SSA.

Considerations of how soil characteristics can be integrated in field-specific fertilizer management in SSA

Spatial characterization and the distribution of rice soils were studied both worldwide (Haefele, Nelson & Hijmans, 2014) and within SSA (Haefele et al., 2013; Saito et al., 2013). Haefele et al. (2014) and Saito et al. (2013) both pointed out that rice-producing soils in SSA are generally poor compared with those in Asia, as represented by the small nutrient-holding capacity or low effective cation exchange capacity, high P fixation, and potential Fe and Al toxicities. Saito et al. (2013) further concluded that these 'very poor rice soils' were dominant particularly in rainfed production systems and from sub-humid to humid environments in East Africa compared with the irrigated lowlands in semiarid to arid regions of West Africa. Tsujimoto, Muranaka, Saito and Asai (2014) also reported that the Si-supplying capacity of soils is poor in SSA, particularly in the sub-humid to humid environments of East Africa.

Efforts to link spatial soil variations to specific fertilizer management practices have been carried out for rice production in SSA since 1990s. First, diagnostic nutrition trials were conducted to assess indigenous N, P, and K supply from soils and responses of rice to fertilizer inputs for irrigated lowlands in West Africa (e.g., Haefele & Wopereis, 2005). The empirical results and mechanistic understanding of soil-plant nutrient dynamics have been integrated into simulation models to determine variety-, site-, and season-specific fertilizer management practices (Haefele & Wopereis, 2004; Haefele, Wopereis, Ndiaye & Kropff, 2003; Segda, Haefele, Wopereis, Sedogo & Guinko, 2005). These research achievements contributed to the implementation of efficient fertilizer management practices at national or subnational scales and to increases in fertilizer input and rice yields in irrigated lowlands in West Africa. However, these studies did not allow for field-specific fertilizer recommendations for individual farmers nor did they address rainfed production systems in which field-to-field variations in both soils and hydrology are much greater than in irrigated lowlands.

Recent progress in field-specific fertilizer management has included development of decision support tools by integrating farmers' individual information on their fields with crop models for calculating fertilizer requirements using their smartphone or tablet. RiceAdvice is one such decision support tool for lowland rice production in SSA (Saito & Sharma, 2018; https://www.riceadvice.info/en/). Using such decision support tool, Saito, Diack, Dieng and N'Diaye (2015b) demonstrated significantly greater fertilizer use efficiencies and economic returns by tailoring fertilizer recommendations to the needs of individual farmer's fields in irrigated lowlands of the Senegal River valley. They attributed these improvements to K application and to the timing and number of N applications.

However, a challenge has remained how to integrate individual soil characteristics with field-specific fertilizer management practices. In reality, the relationship between soil properties and responses to fertilizer input in the field is not straightforward. This is particularly true for lowland rice production systems because biological and chemical reactions of soils are complex under flooded conditions. Hence, there is a need to conduct time-consuming and costly nutrient omission trials for a period of 1–2 years to calculate the nutrient-supplying capacity of soils for regions in which the tools have been newly introduced. Haefele and Wopereis (2005) pointed out that installation of omission plots in each field would not be feasible for most small-scale farmers in SSA and might offset the possible gains from field-specific fertilizer management practices.

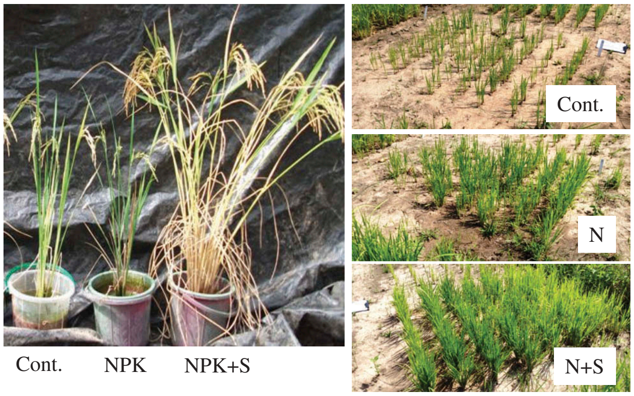

Figure 3. Significant responses to S application in S-deficient soils in the rainfed lowland of northern Ghana.

In this regard, quickly measurable and reliable soil properties or other environmental factors correlating with the responses of rice to fertilizer inputs can extend the model applicability. Our recent study identified large field-to-field variations in responses to N input as a function of the amounts of oxalated-extractable Al and Fe in soils, even among nearby fields of the typical P-deficient lowlands in the central highland of Madagascar (Nishigaki et al., 2019). This result implies that the benefits and applicability of decision support tools can be extended by integrating individual soil variations within a small area even in irrigated lowlands. Further analysis from a systematic nutrient omission trials on N, P, and K across SSA (totaling 1037 farmers' fields in 17 countries, Saito et al., 2019) is expected to improve the understanding on the relationship between soil properties and responses to these macro-nutrients in different farmers' management practices and different rice production systems.

Deficiencies in macro- and micro-nutrients apart from N, P, and K

Deficiencies in other macro- and micro-nutrients—apart from those included in commonly applied fertilizers or tested in nutrient omission trials, that is, N, P, and K—should also be considered when optimizing field-specific fertilizer management practices. Many investigators have noted that various types of macro- and micro-nutrient deficiencies, such as S, Si, and zinc (Zn), can inhibit AE_N for rice production in the 'very poor soils' of SSA (e.g., Bado, Djaman & Valère, 2018; Tsujimoto et al., 2013, 2014; Buri, Masunaga & Wakatsuki, 2000; Figure 3, Table 1). Three-year field experiments demonstrated that AE_N could be nearly doubled, that is, from 13 to 23, by simply applying S to floodplain lowlands in northern Ghana (Tsujimoto et al., 2017). In subsequent on-farm trials under farmers' management practices, AE_N values were also largely increased from 7 to 13 by applying S fertilizer (unpublished). These experiments further verified that greater economic returns are possible if urea (a cheap N source) is mixed with ammonium sulfate (source of S) compared with the application of urea or ammonium sulfate alone. This selective S-added fertilizer management can be to some extent beneficial for rice production in West Africa where such S-deficient soils are widely reported (e.g., Buri et al., 2000). Application of S also significantly improved AE_N, that is, from 8 to 17, in irrigated lowlands in Ethiopia (Habtegebrial, Mersha & Habtu, 2013). Audebert and Fofana (2009) reported significant increases in AE_N from 6 to 11 with Zn application in their 5-year trial in irrigated lowlands of Côte d'Ivoire. They attributed the effect of Zn to the alleviation of iron toxicity. As noted above, Si deficiency can be another AE_N-restricting factor in highly weathered soils in SSA, particularly in the sub-humid to humid environments of East Africa (Tsujimoto, Homma & Shiraiwa, 2010; Tsujimoto et al., 2014). On-farm trials under farmers' management practices in the central highland of Madagascar revealed that Si application as a silica gel significantly increased AE_N, on average, from 5 to 10 in the rainfed uplands and from 8 to 12 in the irrigated lowlands. These empirical evidences imply the AE_N can be improved by understanding spatial variations in these macro- and micro- nutrient deficiencies in SSA soils.

Currently, an increasing number of SSA soil database for N, P, K, and other macro- and micro-nutrients are available in continent-wide and high-resolution scales. Iron toxicity map for rice production across SSA is one of those and recently developed (van Oort, 2018). This is attributable to international initiatives such as the Africa Soil Information Service (http://africasoils.net/) and the development of simplified evaluation technologies using spectrometry and remote-sensing data along with machine learning (Forkuor, Hounkpatin, Welp & Thiel, 2017; Hengl et al., 2017; Kawamura et al., 2019, 2017; Towett, Shepherd, Sila, Aynekulu & Cadisch, 2015). Of course, more empirical evidence must be obtained to correlate specific soil properties with agronomic responses to fertilizer input for rice at different scales to confirm the applicability of these spatial soil information. Then, the information can contribute to accessibility and profitability for smallholder farmers to apply field-specific fertilizer management practices on their own fields and to the improvement of AE_N for rice production in SSA.

Effects of SOC and soil texture in rainfed production systems on AE_N

SOC content and clay content can be another specific soil properties that can be correlated with AE_N for rice particularly in rainfed production systems. In general, the SOC content of croplands tends to be low in SSA, particularly in West Africa compared with the other tropical soils as attributed to high temperature, prevailing coarse-textured soils, low fertilizer input, and low annual biomass production (Zomer, Bossio, Sommer & Verchot, 2017).

Previous studies that mostly focused on upland crops indicated that both SOC and soil texture play essential roles in not only biomass production but also the enhancement of fertilizer use efficiency in the poor soils of SSA (Vanlauwe et al., 2011; Wopereis et al., 2006; Zingore, Murwira, Delve & Giller, 2007). These authors argued that a certain minimum level of SOC and clay content is required for crops to respond well to fertilizer input even under adequate soil moisture conditions. A greater content of SOC and clay increases both soil aggregation and total porosity which contributes to the improvement of field hydrology (e.g., Weil & Magdoff, 2004), and thus increase AE_N in rainfed production systems. In addition, both SOC and clay enhance the nutrient-holding capacity of soils. As a result, higher SOC and clay contents can help supplying other macro- and micronutrients, then improve AE_N.

These positive functions of SOC or clay content for improvement of fertilizer use efficiency have also been observed for rainfed lowland rice production. In the rainfed and floodplain ecosystem of the White Volta River in Ghana, we confirmed a higher AE_N trend for rice in the range of 4.0 to 32.6 kg kg^{-1}, particularly when the content of SOC and clay was above 13.3g kg^{-1} and 18.7%, respectively, by conducting 3-year trials in fields of varying topography (Tsujimoto et al., 2017). This tendency—greater AE_N for soils with higher SOC and clay contents—was also observed when rice was grown in continuously irrigated pots (Tsujimoto et al., 2013). Similarly, Mochizuki et al. (2006) demonstrated a doubling of AE_N from 14 to 31 kg kg^{-1} by simply incorporating clay-rich pond sediment into the sandy fields of gradually sloped rainfed inland valleys of Northeast Thailand: soil amendment with this clay-rich pond increased the clay content from 9% to 19%. Niang et al. (2018) also indicated that sandy soils could be an indicator for low response of rice to N fertilizer input in rainfed production systems.

The content of SOC or clay can differ even among adjacent fields depending on topography and farmers' management practices. Topography-dependent differences in soil properties can be suitable for integration into field-specific fertilizer management practices because geographical information for individual fields can now be collected rapidly and accurately at relatively low cost using an unmanned aerial vehicle, in comparison with conventional soil chemical analysis or on-farm nutrition trials. A simplified SOC estimation method using a soil color sensor can also be used onsite, for its applicability to lowland soils has been demonstrated in Japan (Moritsuka, Matsuoka, Katsura, Sano & Yanai, 2014) and northern Ghana (Katsura et al., 2018). Moreover, there is the opportunity to integrate farmers' perceptions of the color and texture of their soil into field-specific fertilizer management practices (Saito, Linquist, Keobualapha, Shiraiwa & Horie, 2006). The benefits of field-specific fertilizer management based on these farmers' perceptions and topographical information should be further investigated.

Socioeconomic opportunities for increases in fertilizer use and efficiencies

Recent investments in fertilizer blending facilities to tailor nutrient formulations to specific applications should be a positive aspect of realizing the goal of effective and specific fertilizer management practices for rice production in SSA. According to AfricaFertilizer.org (available at https://africafertilizer.org/wp-content/uploads/2018/02/2018_AFO_SSA_Fertilizer_Plants_Register-min-ilovep.pdf), 25 new fertilizer blending facilities have opened or are expected across SSA countries during the period 2017–2019, in addition to the 53 facilities as of 2016. In Madagascar, domestic production of ammonium sulfate has started as the by-product of the nickel-cobalt metal production process and provided a relatively cheap source of both N and S fertilizer since 2015. Therefore, selective application of ammonium sulfate into S-deficient fields should be more cost-effective than blanket application of urea in Madagascar. Secondary-nutrient blended compound fertilizer such as NPK+S and NPK+Zn are yet costly but getting more available in some SSA countries. Foliar fertilizers are less available while the evidence for its cost-effectiveness relative to the direct application into soils has been reported such a case to alleviate Zn deficiency for crop production including rice in SSA (de Valença, Bake, Brouwer & Giller, 2017; Joy et al., 2015).

Effective use of organic resources, for example, crop residue, farmyard manure, animal dropping, can be another option for smallholder farmers to increase AE_N by replenishing SOC and soil nutrient balances such as Si deficiency in a sustainable manner. For the lowland rice production systems, the SRI (System of Rice Intensification)-practicing farmers in the central highland of Madagascar could be regarded as a successful case of organic fertilizer management (Tsujimoto, Horie, Randriamihary, Shiraiwa & Homma, 2009). Barison and Uphoff (2011) observed greater physiological N use efficiency (grain yield per unit N uptake) in SRI-practicing fields relative to conventional fields by comparing 109 farmers in Madagascar who applied both techniques in their different fields. Barison and Uphoff (2011) implied that balanced macro- and micro-nutrient supplies improved physiological N use efficiency in the SRI-practicing fields.

These chemical fertilizer and organic inputs combined with aforementioned soil and hydrologic information should increase opportunities and profitability to apply field-specific fertilizer management practices and contribute to the improved AE_N for rice production in SSA. Cost-benefit analysis should be further needed because the costs and accessibility for both fertilizer options and field information largely differ among sites, countries, and regions.

Improvement of AE_N with small-dose fertilizer supplementation

Development of effective fertilizer application techniques is another key component to improve AE_N and fertilizer profitability. Small-dose and localized fertilization techniques could potentially be adopted by resource-limited smallholder farmers particularly in the areas of SSA where intensive labor inputs are available. These techniques include P dipping to seedling roots at transplantation (De Datta, Biswas & Charoenchamratcheep, 1990) and inclusion of P in planting holes at seed dibbling (Vandamme et al., 2018). As noted above, the latter technique has been practiced by farmers in upland rice production in the central highland of Madagascar. In this section, we focus on the applicability of small-dose fertilizer application to a nursery bed and its effectiveness to improve AE_N under different soil conditions.

Previous studies suggest that the application of small-dose nutrient resources to a nursery bed increases rice yields, especially for nutrient-deficient soils (Ros, Bell & White, 1997; Ros, White & Bell, 2015; Vandamme, Wissuwa, Rose, Ahouanton & Saito, 2016). Ros et al. (2015) demonstrated that fertilizer application to nurseries increased rice yield in the low-fertility, sandy lowlands of Cambodia, reporting yield gains of 0.09–0.21 t ha^{-1} under well-watered conditions and 0.18–0.32 t ha^{-1} under water-stressed conditions. The amount of fertilizer applied to the nursery bed was equivalent to merely 2.7 kg N per hectare in the main field, which resulted in substantially high AE_N (33–78 kg kg^{-1} and 67–119 kg kg^{-1} in well-watered and water-stressed conditions, respectively), as estimated from the ratio of seeding density to the transplanted density (see *Estimated AE_N with microdose application technique* in Table 1). For the typical P-deficient irrigated lowlands of West Africa, Vandamme et al. (2016) reported yield increases of 10–14% with small-dose application to nursery beds at the corresponding rates of 5 kg N ha^{-1}, 3 kg P ha^{-1}, and 5 kg K ha^{-1} in the main field. They also reported an even more pronounced effect of small-dose fertilizer application when soil P deficiency was severe, with yield increases of 30–40%, which provided AE_N at 110–150 kg kg^{-1} as a result of mitigation P-deficiency stress. The results imply that the small-dose NPK application to nursery beds could be more profitable when combined with information on P-deficiency status. It should be noted that these AE_N values are rough estimates from the ratio of seeding density to transplanting density and that AE_N values can widely fluctuate when N application rates are low. Yet, these studies demonstrate that large opportunities exist for increasing AE_N by adopting small-dose application in nurseries, particularly in the nutrient-deficient soils of SSA.

Rice cultivation in SSA is seriously undermined not only by nutrient-deficient soils but also by abiotic stresses at the initial growth stage (Seck et al., 2013). In this respect, the improvement of seedling quality by optimizing nutrient management in the nursery has been documented as an effective measure to overcome abiotic stresses such as submergence (Bhowmick, Dhara, Singh, Dar & Singh, 2014; Ella & Ismail, 2006; Jackson & Ram, 2003; Ram et al., 2009; Singh, Hong, Sharma & Dhanapala, 2004), salinity (Sarangi et al., 2015), and drought stress (Ros et al., 2015). Panda, Reddy and Sharma (1991) demonstrated the large yield gains by 0.4–2.1 t ha^{-1} and AE_N at 40–210 kg kg^{-1} with the nursery application of 100 kg N ha^{-1} (roughly equivalent to 10 kg N ha^{-1} in main field) at submergence-prone fields in the initial growth stage. In the case of high-salinity soils in coastal areas, Sarangi et al. (2015) reported a yield gain of up to 1.0 t ha^{-1} with nursery application of 50 kg N ha^{-1} (equivalent to 3.5 kg N ha^{-1} in main field). These facts also suggest that small-dose fertilizer application to nurseries can benefit resource-limited smallholder farmers in SSA.

Further agronomic studies on nutrient management practices under climate change

Further studies are needed concerning the effects of nutrient management practices on yield and AE_N under different regional climate conditions. The impact of both climate change and suboptimal nutrient management practices on rice production in SSA has been studied intensively, but each separately (e.g., van Oort, 2018; van Oort & Zwart, 2018; and many studies cited in

Figure 4. Significant effect of P application on phenological development in an irrigated lowland area of the central highland of Madagascar.

our current review). Nonetheless, some of the experimental results imply a significant effect of nutrient management practices on the risks of climate-induced stress with respect to rice production. For instance, Njinju et al. (2018) carried out three-season field experiments in the highlands of Kenya, where the daily minimum temperature was below 18ºC in the middle-to-late growth stages. They consistently observed that N application of >75 kg ha^{-1} linearly reduced rice grain fertility and resulted in significant yield reductions of up to 60% for certain varieties such as IR64 and Basmati370. The results imply that AE_N can be negative when overdose N and cold-induced stress are combined. These field-based results, demonstrating significant impacts of N management on climate-induced stresses, should attract further attention with respect to considering improved AE_N for rice production in SSA.

Interaction between P deficiency and climate-induced stresses may also affect AE_N for rice production. Our preliminary field trials demonstrated significant delays in phenology development under P-deficient conditions in the central highlands of Madagascar—heading was delayed by more than 3 weeks in P-deficient plots (Figure 4). This phenological response of rice to P deficiency could potentially have a positive effect on grain yield, that is, by extending the growth period. However, delayed heading may also increase the risk of cold-induced sterility later in the growth stage, which is the case for the main cropping season in the highlands of East and Southern Africa, and waste N inputs. The increased risk of environmental stress that can be attributed to P deficiency-induced delay in phenological development can also be presumed in regions where late-season drought is common. These assumptions imply that appropriate N and P management should not be based solely on field nutrient characteristics; rather, climate conditions, planting period, and duration of varietal growth should also be considered. These interactions between P deficiency and environmental stress have not been considered in any field experiments or model predictions.

Conclusion

By referring to the fact that the ratio of the price of grains to fertilizer has been fairly constant over 20 years in many countries of SSA, Jayne, Mason, Burke and Ariga (2018) noted 'only changes in agronomic response to fertilizer inputs can drive meaningful change in fertilizer profitability', while 'this response is lower than expected under smallholder-managed fields'. In this regard, a key task for agronomic researchers is to address improvements in fertilizer use efficiency in SSA. Evidence is scarce concerning rice production in SSA, whereas the AE_N values we have reported here imply that large gaps remain between researcher-managed and farmer-managed trials even in irrigated lowlands and that there were large spatial variations in different levels from location to location and field to field (Table 1). This review corroborates the general perception that fertilizer management practices must account for variations in soil characteristics and geography to fill this gap in SSA, where smallholder farmers still rely on inherent and heterogeneric field characteristics for their rice production. Accumulated experimental results suggest that AE_N values for rice production could be increased by adjusting not only N, P, and K nutrient status but also other micro- and macro-nutrient deficiencies such as S, Si, and Zn and iron toxicity even under conditions of adequate water management. Our recent observation of highly variable P-deficiency status even among adjacent lowland fields suggests the importance of optimizing site-specific nutrient management practices at a relatively small scale. Geographic parameters in relation to SOC content and field hydrology may be additional key factors for improving field-specific fertilizer management in rainfed production systems. Interactive decision support tools through smartphones/tablets can play a pivotal role in translating soil and geographic information into field-specific fertilizer management practices.

Note

1. FAO (2002) is to our knowledge most recently available data source for fertilizer use by crop and by nutrient element worldwide, but included merely 7 countries in SSA; Kenya, Madagascar, Malawi, Tanzania, Guinea, Mauritania, and Togo.

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